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The Spectral Variability of Cygnus X-1 at MeV Energies

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Abstract. In previous work, we have used data from the first three years of the CGRO mission to assemble a broad-band γ-ray spectrum of the galactic black hole candidate Cygnus X-1. Contemporaneous data from the COMPTEL, OSSE and BATSE experiments on CGRO were selected on the basis of the hard X-ray flux (45–140 keV) as measured by BATSE. This provided a spectrum of Cygnus X-1 in its canonical low X-ray state (as measured at energies below 10 keV), covering the energy range from 50 keV to 5 MeV. Here we report on a comparison of this spectrum to a COMPTEL-OSSE spectrum collected during a high X-ray state of Cygnus X-1 (May, 1996). These data provide evidence for significant spectral variability at energies above 1 MeV. In particular, whereas the hard X-ray flux *decreases* during the high X-ray state, the flux at energies above 1 MeV *increases*, resulting in a significantly harder high energy spectrum. This behavior is consistent with the general picture of galactic black hole candidates having two distinct spectral forms at soft γ-ray energies. These data extend this picture, for the first time, to energies above 1 MeV.

INTRODUCTION

Observations by the instruments on CGRO, coupled with observations by other high-energy experiments (e.g., SIGMA, ASCA and RXTE) have provided a wealth of new information regarding the emission properties of galactic black hole candidates. An important aspect of these high energy radiations is spectral variability, observations of which can provide constraints on models which seek to describe the global emission processes. Based on observations by OSSE of seven transient galactic black hole candidates at soft γ-ray energies (i.e., below 1 MeV), two γ-ray spectral shapes have been identified that appear to be well-correlated with the soft

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X-ray state [1,2]. In particular, these observations define a *breaking* γ-ray spectrum that corresponds to the low X-ray state and a *power-law* γ-ray spectrum that corresponds to the high X-ray state. (Here we emphasize that the 'state' is that measured at soft X-ray energies, below 10 keV.)

At X-ray energies, the measured flux from Cyg X-1 is known to be variable over a wide range of time scales, ranging from msec to months. It spends most of its time in a low X-ray state, exhibiting a breaking spectrum at γ-ray energies that is often characterized as a Comptonization spectrum. In May of 1996, a transition of Cyg X-1 into a high X-ray state was observed by RXTE, beginning on May 10 [3]. The 2–12 keV flux reached a level of 2 Crab on May 19, four times higher than its normal value. Meanwhile, at hard X-ray energies (20-200 keV), BATSE measured a significant *decrease* in flux [4]. Motivated by these dramatic changes, a target-of-opportunity (ToO) for CGRO, with observations by OSSE, COMPTEL and EGRET, began on June 14 (CGRO viewing period 522.5). Here we report on the results from an analysis of the COMPTEL data from this ToO observation.

OBSERVATIONS AND DATA ANALYSIS

COMPTEL has obtained numerous observations of the Cygnus region since its launch in 1991, providing the best available source of data for studies of Cyg X-1 at energies above 1 MeV. Figure 1 shows a plot of hard X-ray flux, as obtained from BATSE occultation monitoring, for each day in which Cyg X-1 was within 40° of the COMPTEL pointing direction.

In previous work, we have compiled a broad-band spectrum of Cyg X-1 using contemporaneous data from BATSE, OSSE and COMPTEL [5,6]. The observations were chosen, in part, based on the level of hard X-ray flux measured by BATSE, the goal being to ensure a spectral measurement that corresponded to a common spectral state. In Figure 1, the data points from the selected observations are indicated by open diamonds. The resulting spectrum, corresponding to a low X-ray state, showed evidence for emission out to 5 MeV. The spectral shape, although consistent with the so-called breaking spectral state [1,2], was clearly not consistent with standard Comptonization models. The COMPTEL data provided evidence for a hard tail at energies above $\sim$1 MeV that extended to perhaps 5 MeV.

During the high X-ray state observations in May of 1996 (VP 522.5), COMPTEL collected 11 days of data at a favorable aspect angle of 5.3°. The hard X-ray flux for these days is denoted by open triangles in Figure 1. An analysis of COMPTEL data from this observation revealed some unusual characteristics. The 1–3 MeV image (Figure 2) showed an unusually strong signal from Cyg X-1 when compared with other observations of similar exposure. The flux level was significantly higher than the average flux seen from earlier observations [5,6]. In the 1–3 MeV energy band, the flux had increased by a factor of 2.5, from $8.6(\pm 2.7) \times 10^{-5}$ cm^{-2} s^{-1} MeV^{-1} to $2.2(\pm 0.4) \times 10^{-4}$ cm^{-2} s^{-1} MeV^{-1}. The observed change in flux is significant at a level of 2.6σ. In addition, unlike in previous measurements, there

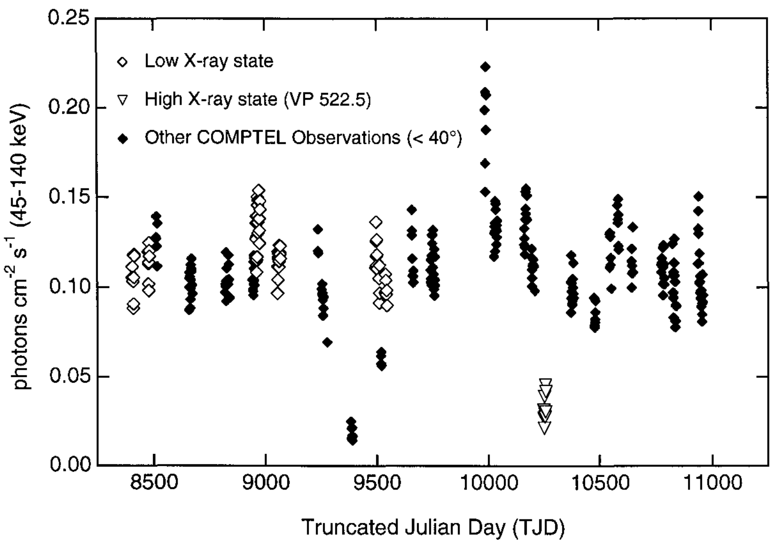

FIGURE 1. Hard X-ray time history (from 45–140 keV BATSE occultation data) for COMPTEL observations of Cyg X-1. Open diamonds indicate those data used to generate the low-state γ-ray spectrum. Open triangles correspond to CGRO viewing period 522.5.

was no evidence for any emission at energies *below* 1 MeV. This fact is explained, in part, by a slowly degrading sensitivity of COMPTEL at energies below 1 MeV due to increasing energy thresholds in the lower (D2) detection plane. Part of the explanation, however, appears to be a much harder source spectrum.

A more complete picture of the MeV spectrum is obtained by combining the COMPTEL results with results from OSSE, extending the measured spectrum down to $\sim$50 keV. Unfortunately, a comparison of the COMPTEL and OSSE spectra for VP 522.5 shows indications for an offset between the two spectra by about a factor of two, with the OSSE flux points being lower than those of COMPTEL in the overlapping energy region near 1 MeV. A similar offset between OSSE and COMPTEL-BATSE is also evident in the contemporaneous low soft X-ray state spectrum [5,6]. The origin of this offset is not clear. Here we shall assume that there exists some uncertainty in the instrument calibrations and that this uncertainty manifests itself in a global normalization offset. We have subsequently increased the flux for each OSSE data point by a factor of two. This provides a good match between COMPTEL and OSSE at 1 MeV for both the low-state and high-state spectra, but we are left with an uncertainty (by a factor of two) in the absolute normalization of the spectra.

We compare the resulting COMPTEL-OSSE spectra in Figure 3 (with the data points in both OSSE spectra increased by a factor two). The low-state spectrum shows the breaking type spectrum that is typical of most high energy observations

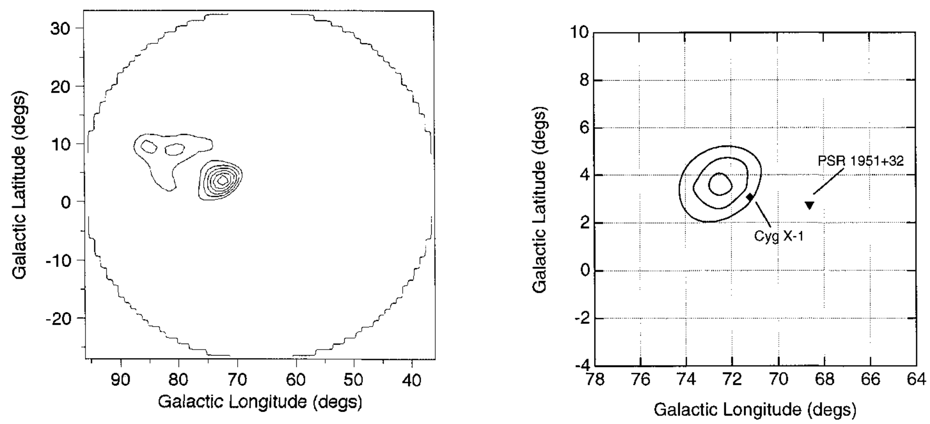

FIGURE 2. COMPTEL imaging of the Cygnus region as derived from 1–3 MeV data collected during high X-ray state of VP 522.5. The left-hand figure shows the maximum likelihood map. The right-hand figure shows the 1, 2 and 3-σ location contours. The emission is consistent with a point source at the location of Cyg X-1, with no significant contribution from PSR 1951+32.

of Cyg X-1. The high-state spectrum, on the other hand, shows the power-law type spectrum that is characteristic of black hole candidates in their high X-ray state. This spectral behavior had already been reported for this time period based on observations with both BATSE [7] and OSSE [8]. The inclusion of the COMPTEL data provides evidence, for the first time, of a continuous power-law (with a photon spectral index of -2.6) extending beyond 1 MeV, up to ~10 MeV.

A power-law spectrum had also been observed by both OSSE and BATSE during February of 1994 [9,10], corresponding to the low level of hard X-ray flux near TJD 9400 in Figure 1. In this case, however, the amplitude of the power-law was too low for it to be detected by COMPTEL.

DISCUSSION

We can use the COMPTEL data alone to draw some important conclusions regarding the MeV variability of Cyg X-1. Most importantly, the flux measured by COMPTEL at energies above 1 MeV was observed to be higher (by a factor of 2.5) during the high X-ray state (in May of 1996) than it was during the low X-ray state. The lack of any detectable emission below 1 MeV further suggests a relatively hard spectrum.

Inclusion of the OSSE spectra clearly show an evolution from a breaking type spectrum in the low X-ray state to a power-law spectrum in the high X-ray state. The COMPTEL data are consistent with a pivot point near 1 MeV. The power-law appears to extend to ~10 MeV with no clear indication of a cut-off.

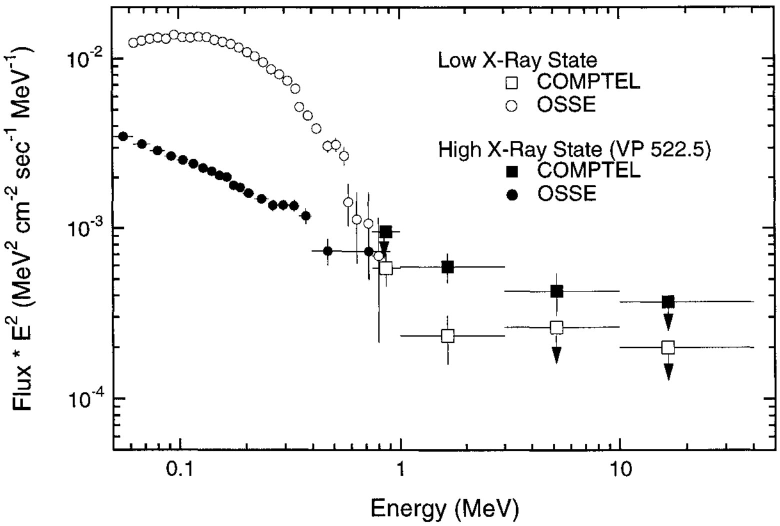

FIGURE 3. Spectra of Cyg X-1, shown as E^2 times the photon flux. OSSE flux levels have been increased by a factor of two and OSSE upper limits have been removed for the sake of clarity.

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